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Fabrication of 2×8 Power Splitters in Silica-on-Silicon by the Direct UV Writing Technique

M. Olivero and M. Svalgaard

Abstract—In this letter, we present the first demonstration of 2×8 power splitters made in silica-on-silicon by direct ultraviolet (UV) writing. The fabricated components are compact and exhibit good performance in terms of loss, uniformity, and bandwidth, showing that direct UV writing can become a competitive technology for fabrication of low-cost integrated optical devices.

Index Terms—Direct ultraviolet (UV) writing, optical device fabrication, optical devices, optical planar waveguide components.

I. INTRODUCTION

COMPACT, low-cost integrated optical components play a crucial role to the continued deployment of optical communication technologies. Among the latter, passive optical networks for fiber-to-the-home applications are expected to experience a rapid growth in the near future. Passive optical networks require $2 \times N$ optical splitters, in order to create redundant paths and increase the network security [1].

Fabrication techniques using photolithography and etching yield high-quality components, however, the expenses required to set up and maintain production facilities are large. For this reason the direct ultraviolet (UV) writing technique [2] represents an interesting alternative for fabrication of low-cost integrated optical devices. In this technique, waveguides are written directly into a photosensitive glass sample with a focused UV laser, thereby avoiding expensive photolithographic and etching-based fabrication steps. Up to date, the only demonstration of a commercially interesting UV written device is a variable optical attenuator [3], which has a limited complexity of the layout. In this letter, the development of compact, low loss, uniform, and broad-band 2×8 optical splitters by means of direct UV writing is reported. The components consist of a broad-band asymmetrical coupler followed by Y-branch splitter sections and feature a total excess loss of 1.6 dB and a channel uniformity of 1.9 dB over a wavelength range of 1400–1700 nm.

II. DEVICE FABRICATION

The splitters are fabricated in three-layer silica-on-silicon samples with a 5.4- μm -thick Ge-B-doped core layer. The three

layers are index matched within $\pm 5 \times 10^{-4}$ to yield a circular mode profile [4]. The samples are loaded with deuterium at 500 bar until saturation prior to UV writing to enhance the photosensitivity [5].

Waveguides are written into the core layer by scanning the sample under a continuous-wave focused UV beam using high-precision translation stages. The experimental setup is similar to that used in earlier work [3], except for the fact that the scanning accuracy has recently been improved by means of interferometric position feedback [6]. The UV beam has a wavelength of 257 nm and may be blocked using a shutter as required in the scanning process. The incident beam power is 45 mW, which is focused on the core layer to a $1/e^2$ spot size of 3.1 μm . Most of the waveguide circuit is written with a scan velocity of 280 $\mu\text{m/s}$, except for selected regions in the central part of the coupler and Y-branch sections, as detailed later. The resulting waveguide width is 6.0 μm . After UV writing, the samples are subjected to two annealing steps. The first is carried out at 80 °C for 12 h to outdiffuse residual deuterium without inducing the formation of oxygen-defect centers. In order to achieve single-mode operation in both the 1300- and 1500-nm windows, an extra annealing is required to reduce the index step. This is done by annealing at 320 °C for 3 h, thereby reducing the index step from 0.014 to 0.0085. Achieving the desired index step by high-temperature annealing rather than by adjusting the UV power or scan velocity ensures a high degree of long-term stability of the induced index step [7].

III. CIRCUIT LAYOUT

The layout of the fabricated 2×8 splitters is depicted in Fig. 1(a). Two input channels are combined through an asymmetrical broad-band directional coupler [6], which is written in two scans. An asymmetric structure in the central coupling region is achieved by decreasing the scan velocity in the first arm while increasing it in the second arm. Scan velocities of 100 and 900 $\mu\text{m/s}$, a center-to-center waveguide separation of 8- and 230- μm -long waveguides in the central coupling region result in a wavelength flattened 3-dB coupling ratio [6].

Each output of the coupler connects to a cascade of Y-shaped splitting sections. Each Y-branch is written in three scans, first the access waveguide followed by two output arms [Fig. 1(b)]. The output arms are shaped as a cascade of two S-bends: The first to make an adiabatic taper and the second to achieve the required displacement to connect to the next section. Each S-bend is shaped as a polynomial function with null derivatives up to the third order at the boundaries, in order to minimize mode mismatching with the connecting waveguides. The bend lengths have been chosen so that the minimum radius of curvature is

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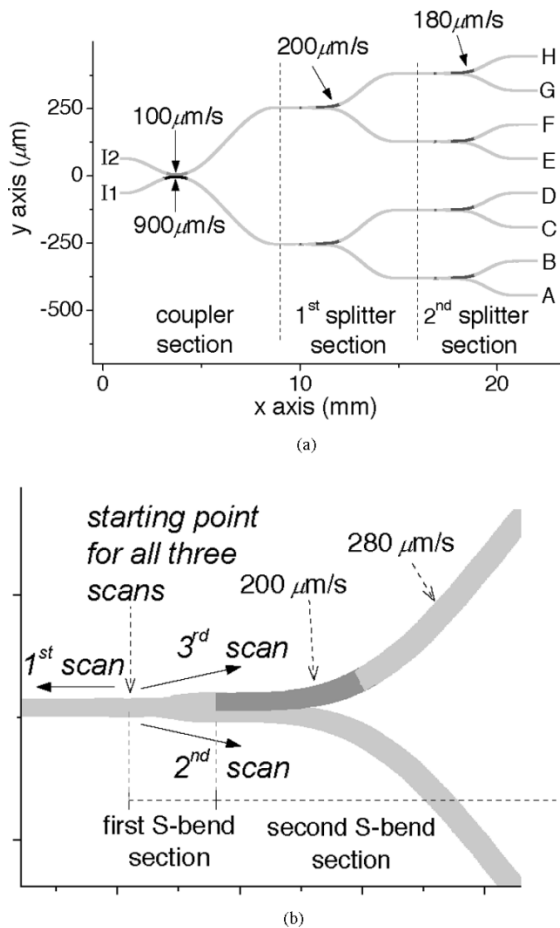


Fig. 1. (a) Overview of 2×8 splitter layout. (b) Close-up view of a Y-branch in first splitter section (solid arrows indicate the scan directions). The gray shades indicate the applied scan velocity in the different waveguide sections.

20 mm, yielding an excess loss measured on concatenated bends of ~ 0.05 dB/bend. Symmetrical splitting is achieved by applying slightly different scan velocities in the central part of each splitter [Fig. 1(b)], to compensate for a reduced photosensitivity in the vicinity of a UV exposed area [8]. The required amount of compensation depends on the geometry of the branching point; i.e., ultimately by the desired arm separation. Using the standard scan velocity of $280 \mu\text{m/s}$ in the first arm, we experimentally found that the optimum scan velocities in the second arm, to achieve 3-dB splitting, are $200 \mu\text{m/s}$ for the first splitting section and $180 \mu\text{m/s}$ for the second splitting section.

The output port pitch is $127 \mu\text{m}$ to accommodate commercially available fiber connector arrays. The component length is 22 mm which, combined with 10-mm-long fiber connector arrays, would yield a pigtailed device that would be roughly 2/3 the size of many commercially available components, and thus is very well suited for compact system integration. The total UV writing time for a single 2×8 splitter is 360 s, yielding a theoretical production capacity of ~ 240 components per day.

IV. PERFORMANCE

Characterization was carried out with butt-coupled SMF-28 fibers and index-matching oil, using either a polarized 1557-nm source or an unpolarized broad-band source from 1300 to

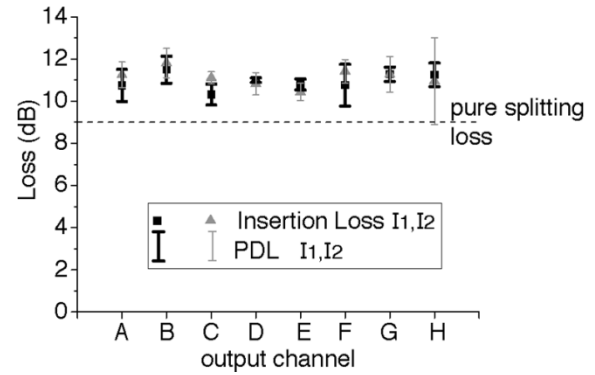


Fig. 2. Insertion loss (symbols) and PDL (bars) of a typical 2×8 splitter measured at 1557 nm.

1750 nm. Insertion loss and polarization-dependent loss (PDL) at 1557 nm were measured with an automatic loss meter EXFO IQ-3400, while insertion loss over broad-band range was measured with an optical spectrum analyzer. Straight waveguides on a 34-mm-long sample exhibit a total insertion loss of 0.3 dB and PDL equal to our setup detection limit of 0.2 dB. A coupling loss of ~ 0.03 dB/facet was extrapolated from measurement of waveguides with decreasing length. Index step, width, and loss measurements on waveguides written on different samples over several months consistently remain within the measurement uncertainty ($\pm 5\%$), thereby indicating the robustness of the fabrication process. In addition, the reproducibility of 3-dB branching sections has been investigated by characterizing a large number of devices fabricated on different samples over a period of three months. The average splitting ratio did not show any trend over this time period and the splitting ratio standard deviation (due to fabrication imperfections) was measured to be 0.2 dB, again demonstrating the robustness of the UV writing process.

The typical insertion loss and PDL at 1557 nm for each output channel of a 2×8 splitter is summarized in Fig. 2. The dataset for each input port overlap each other and do not exhibit any slope, showing that the coupling and splitter sections are well balanced. The channel loss is < 11.6 dB and the total excess loss is 1.4 dB, which is similar to that of commercial devices. The average PDL is 0.6 dB, but for channel H it rises to 2 dB with excitation at I_1 . This phenomenon is seen in many of the fabricated devices and it does not occur for the same input-output channel each time. The effect only becomes apparent when the guided mode amplitude is low, such as when the input signal is distributed among several output channels [9]. It is speculated that weakly guided vertical modes copropagate in the core layer because the latter may have an index slightly higher than the buffer-cladding, and upon recoupling to the channel waveguide this may lead to the observed behavior [10]. A core layer with a refractive index slightly lower than that of the buffer-cladding could prevent such parasitic vertical resonance and may thus reduce the sporadically high PDL.

The spectral performance of an isolated asymmetric coupler section is depicted in Fig. 3 along with that of a standard symmetrical coupler for comparison. The former exhibits a ± 0.5 -dB flatness over the entire 450-nm wavelength range, whereas the symmetrical coupler exhibits the same variation over just 80 nm.

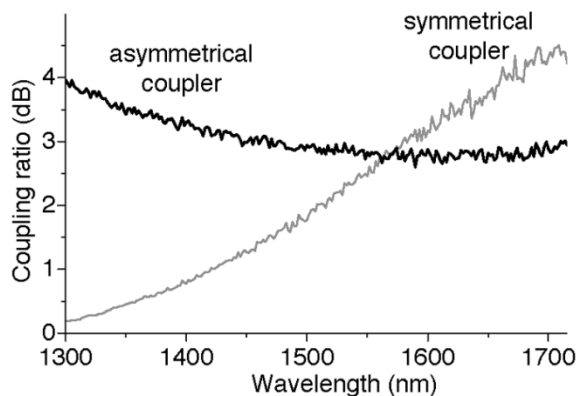


Fig. 3 Spectral variation of the coupling ratio for an asymmetrical and a symmetrical coupler.

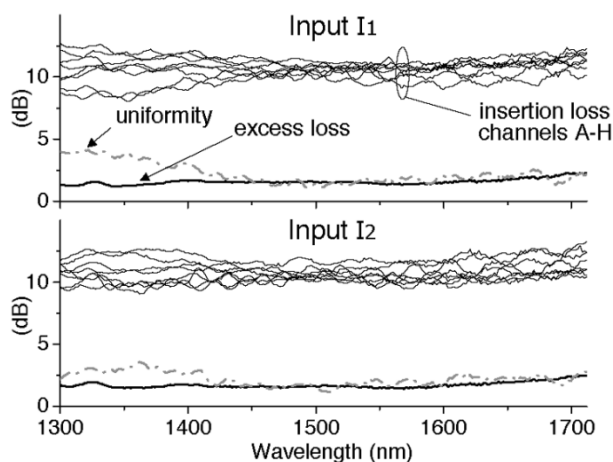


Fig. 4 Broad-band measurement of insertion loss (black curves), uniformity (gray dashed curve, arrowed), and total device excess loss (dark gray solid curve, arrowed) from input I_1 (top), from input I_2 (bottom).

Unlike asymmetrical couplers made with standard photolithography techniques, here the asymmetry, and thus the flattened response, is enhanced by varying both the index step and the width of the coupled waveguides. This improvement follows directly from the nature of UV writing where it is achieved simply by varying the scan velocity [6].

Broad-band measurements of channel loss, uniformity, and total excess loss of a complete 2×8 splitter are shown in Fig. 4. The total excess loss over the entire range is 1.6 dB. The uniformity is quite flat and low down to 1400 nm, with a mean value of 1.9 dB. Below 1400 nm, the uniformity rises, most likely due to the increased slope of the coupling ratio shown in Fig. 3. A further improvement of the uniformity in the 1300-nm window can be achieved by a small optimization of the coupling section, i.e., by shifting the wavelength of minimum coupling ratio from the current ~ 1600 to ~ 1500 nm. The overall broad-band response is similar to that of currently available commercial components in terms of both loss and uniformity in the C -, L -, and E -bands.

The device-to-device fabrication reproducibility is quite good on our research setup with five out of seven measured devices being within the presented specifications. The main source of component failure arises from laser power drift, which is expected to be improved by introduction of an active control of the incident UV power.

V. CONCLUSION

The first demonstration of 2×8 optical power splitters made by the direct UV writing technique has been presented. The splitter layout consists of a broad-band coupler section followed by Y-branch splitter sections and has been optimized for compactness and low loss.

The unique feature of direct UV writing to locally control the index step and width by changing the scan velocity has been exploited to achieve broad-band performance. The scan velocities applied in the splitting sections have been optimized to achieve good uniformity among the output channels. The performance in terms of size, loss, uniformity, and bandwidth is similar to that of currently available commercial components, whereas the problem of sporadically high PDL still has to be addressed. The achieved results suggest that direct UV writing is an interesting alternative for low-cost fabrication of integrated optical devices with increased complexity.

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